X-Ray Characterization of Diesel Sprays

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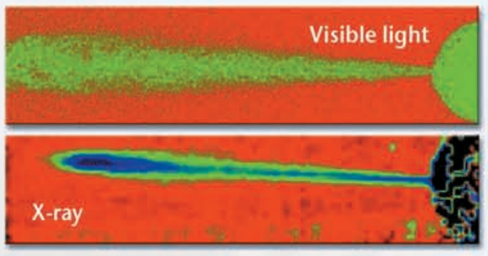
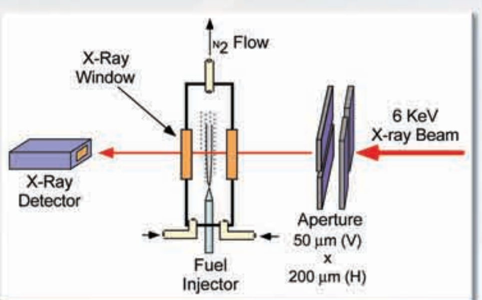
The allowable limits of pollutants emitted from automotive gasoline and diesel engines are being tightened in both the U.S. and Europe. Automakers are looking for ways to improve the emission performance of their engines without sacrificing power and efficiency, which requires a detailed knowledge of the entire combustion process. One of the most critical pieces of information about combustion in engines is also the least understood: the structure and dynamic behavior of fuel sprays.



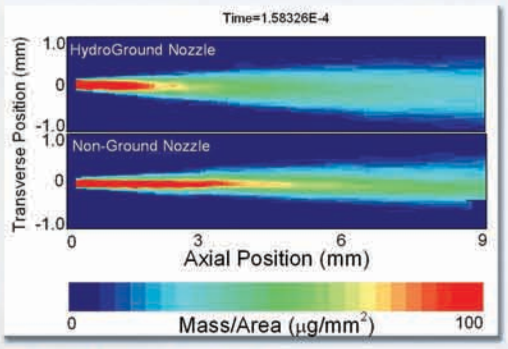
Studies of fuel sprays for the last 25 years have centered on visible light imaging techniques. While these techniques can show the features of a spray at its periphery, they cannot reveal the internal structure. Fuel sprays are composed of many densely-packed droplets, and visible light is unable to penetrate through this fog. X-rays have a low probability of scattering from fuel droplets and are able to penetrate through the spray, enabling quantitative measurements of structure and dynamic behavior.

Here a visible light image of a diesel fuel spray (top) is compared with an x-ray image (bottom). In the visible light image, the color merely indicates the amount of light scattered into the detector from the droplets surrounding the spray. It is impossible to determine quantitative information about the internal structure of the spray from such a measurement. On the other hand, the x-ray image shows the overall fuel distribution within the spray, and the colors indicate the amount of fuel at each position.

Measurements such as these allow us to calculate parameters of the spray that are critical to pollutant formation, such as the volume fraction and the local fuel/air ratio. In addition, detailed measurements such as these give spray modelers a very stringent test of their simulations. Previously, modelers had to make assumptions about the structure of the spray in the region near the nozzle since accurate measurements were not available. These quantitative measurements will allow modelers to develop a better understanding of the complex fluid dynamics that take place in the formation and breakup of a spray. Improvements in spray modeling will speed the time required for manufacturers to develop cleaner-burning, more efficient engines.

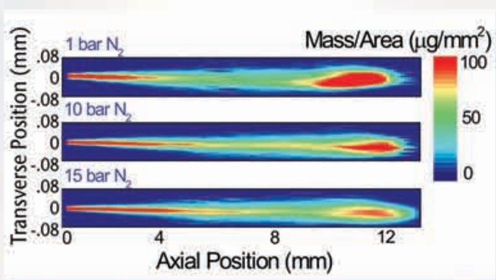


Line-of-sight absorption measurements have been made of sprays from gasoline and diesel fuel injection systems. We used two different detector systems: a focused beam and point detector provide precise spatial resolution, while a beam of extended size and a two-dimensional detector allow us to image larger regions of the spray. The use of monochromatic x-rays allows a straightforward determination of the mass of fuel from the measured x-ray intensity.



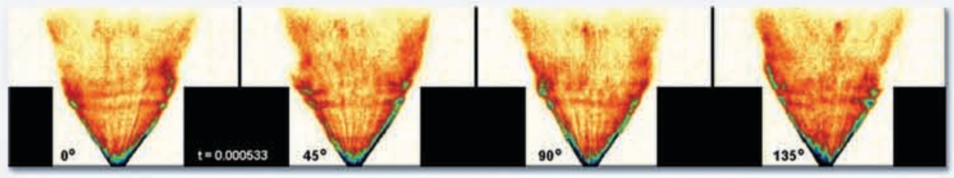
The Effects of Nozzle Geometry

One important factor that strongly influences the structure of the spray is the internal geometry of the spray nozzle. Manufacturers design nozzles with the goal of optimizing spray atomization, penetration, and local fuel-to-air ratio. However, most spray measurement techniques cannot discern the subtle changes in the spray that result from small changes in nozzle design. X-rays are a valuable tool to solve this problem, since they allow measurements in the region near the nozzle where the ambient environment has had little chance to perturb the structure of the spray. Here sprays from nozzles with two different internal geometries are shown. The top image was measured from a nozzle with smooth, rounded corners inside the nozzle, while the bottom image was produced by a nozzle with sharp corners. It can be seen that the sharp-cornered nozzle produced a spray with a high-density core that extends farther from the nozzle. Measurements such as these are critical for spray simulations, which attempt to predict the structure of a spray based on the nozzle design, and also for fuel system manufacturers who wish to quantify the effects of changes to the nozzle geometry.



The Effects of Ambient Pressure

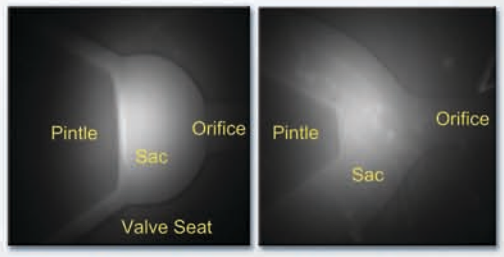
The ambient pressure of the combustion chamber is also an important parameter that affects the structure of the spray, particularly as the spray moves farther from the nozzle. X-ray measurements of the spray's mass distribution allow us to quantify how the ambient environment affects the spray's structure and dynamics. Here measurements of sprays under otherwise identical conditions are shown at three different ambient pressures. It can be seen that for sprays of identical penetration, the sprays penetrating into a lower-pressure environment have larger regions of high density near their leading edge. Also, the sprays under higher ambient pressure show a higher-density core extending farther from the nozzle.



X-Ray Absorption Tomography

With highly asymmetric sprays, it becomes difficult to interpret a single two-dimensional projection. Here, four images of a hollow-cone spray are shown (the injector has been rotated by 45 degrees between each image). "Clumps" and "bands" of high density can be seen at many regions in the images. Measuring several different projections allows a model-dependent three-dimensional reconstruction of the spray to be built. Recent experiments have improved this technique by expanding the number of projections from four to 180, which allows a model-independent construction to be performed to measure the exact three-dimensional mass distribution for this spray.

Special thanks to: Wenyi Cai, Jinyuan Liu, Suresh Narayanan, Yong Yue, Matt Renzi, Alper Ercan, Mark Tate, Sol Gruner



X-Ray Phase Contrast Imaging

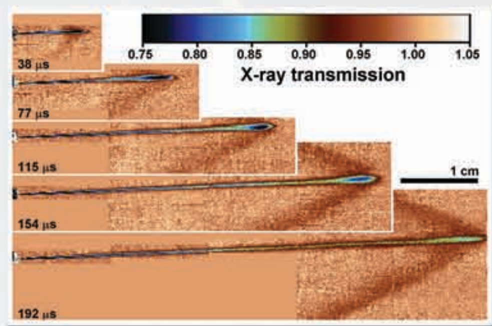
The development of new diagnostic tools using x-rays is a primary role for part of our group and our colleagues. Recently, scientists at the Advanced Photon Source have developed imaging techniques that allow us to peer through the solid steel structure of spray nozzles to see the internal geometry of the valve within. Above are images of two nozzles with different internal geometries. The nozzle on the left has sharp, unfinished corners, while the nozzle on the right has smooth, rounded corners. Recent advances to this technique have allowed us to capture stop-motion images of these injectors in operation, revealing for the first time the opening and closing of the internal valves and eccentricities in the motion of the pintle. Measurements such as these will prove invaluable to spray modelers and injector manufacturers alike.

Special thanks to: Wah-Keat Lee, Kamel Fezzaa

Multi-Layer X-Ray Monochromator

Currently, we are forced to average the measured results from multiple sprays in order to improve our statistical accuracy. We have recently completed the construction of a multi-layer monochromator that will increase our x-ray flux by a factor of 50. This will allow us to make measurements of individual sprays without averaging and observe the variability from one spray to the next. Precise reproducibility is an important feature for fuel system manufacturers, since fuel injectors may fire thousands of times per second and small variations can produce undesired pollutants.

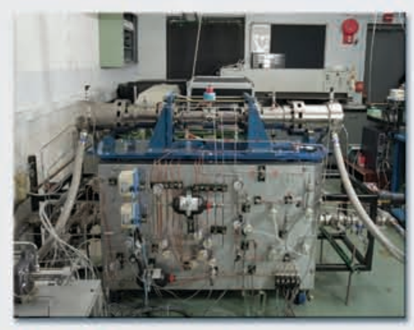
Special thanks to: Suresh Narayanan, Jinyuan Liu, Deming Shu, Yujie Wang



Shock Wave Measurements

Engine manufacturers have been steadily increasing injection pressure in order to improve spray atomization. High-speed sprays can generate shock waves in the ambient gas under certain conditions. Here we have imaged shock waves generated by a high-speed spray using x-ray absorption. Since the absorption is related to the gas density, the measurements can be used to quantify the density of the shock wave. This was the first time shock waves generated by a spray had been observed and quantified.

Special thanks to: Andrew MacPhee, Yong Yue, Suresh Narayanan,Matt Renzi, Alper Ercan, Mark Tate, Ernie Fontes,Sol Gruner, Johannes Schaller, Jochen Walther



Rapid Compression Machine

Modern combustion engines operate under conditions of high pressure and temperature. Currently, we can only simulate sprays under conditions of elevated pressure. We recently completed assembly and testing of a rapid compression machine, which will allow us to measure sprays under conditions similar to those of an operating engine. The machine has been designed to produce minimal vibration to preserve the high precision of our measurements. It will be incorporated into our measurements in fiscal year 2006.

Special thanks to: Jim Bailey, Ed Bielick, Roy Cuenca, Sreenath Gupta, Greg Klett

This work supported by the U.S. Department of Energy under contract W-31-109-Eng-38 and by the FreedomCar & Vehicle Technologies Program. Experiments were performed at the 1-BM Beamline of the Advanced Photon Source, Argonne National Laboratory, and at the Cornell High Energy Synchrotron Source (CHESS). CHESS is supported by NSF agreement DMR-9713424. Detector development is supported by the DOE on grants DE-FG02-97ER14805 and DE-FG02-97ER62443.

Argonne National Laboratory is managed by The University of Chicago for the U.S. Department of Energy